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Chutjian et al.

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[54] **GENERATION OF INTENSE NEGATIVE ION BEAMS**

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[22] Filed: **May 2, 1985**

[51] **Int. Cl.**⁴ **H01J 27/02**

[52] **U.S. Cl.** .... **250/423 R**; 250/424; 250/427; 250/288; 313/359.1; 313/361.1; 313/362.1; 315/111.81

[58] **Field of Search** .... 250/423 R, 424, 425, 250/427, 288; 313/359.1, 361.1, 362.1; 315/111.81

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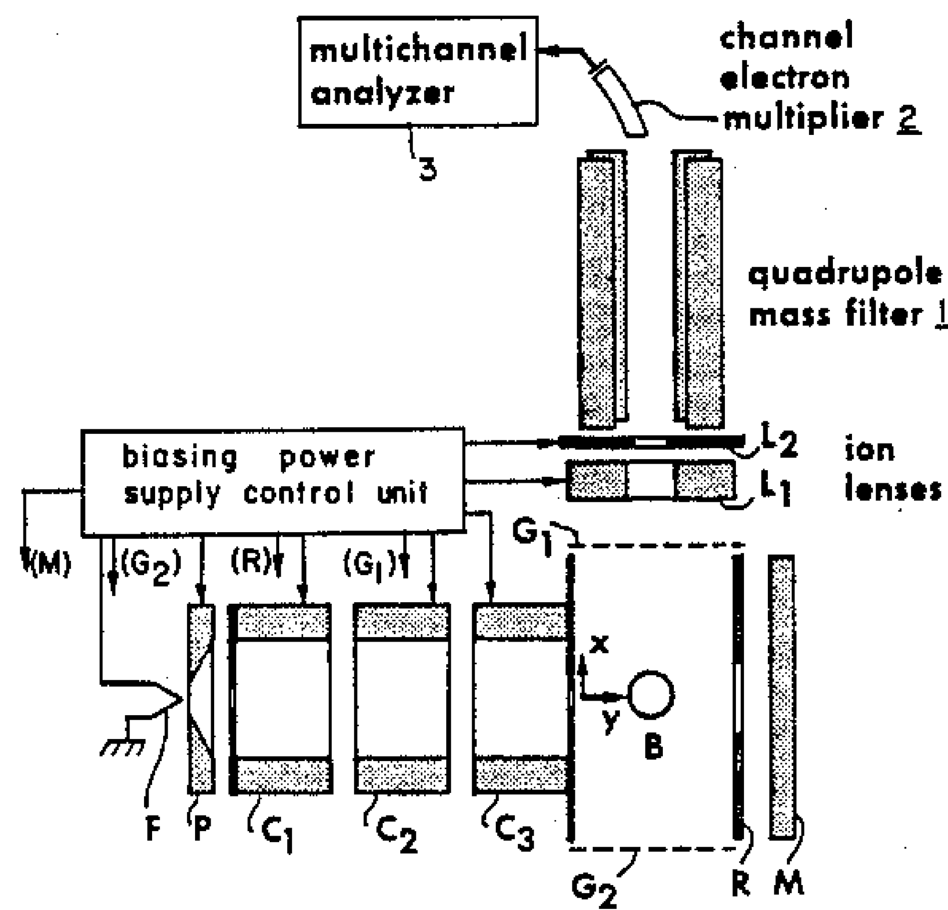
[57] **ABSTRACT**

An electron gun is used with a mirror electrostatic field to produce zero or near zero velocity electrons by forming a turning point in their trajectories. A gas capable of attaching zero or near zero velocity is introduced at this turning point, and negative ions are produced by the attachment or dissociative attachment process. Operation may be continuous or pulsed. Ions thus formed are extracted by a simple lens system and suitable biasing of grids.

12 Claims, 5 Drawing Figures



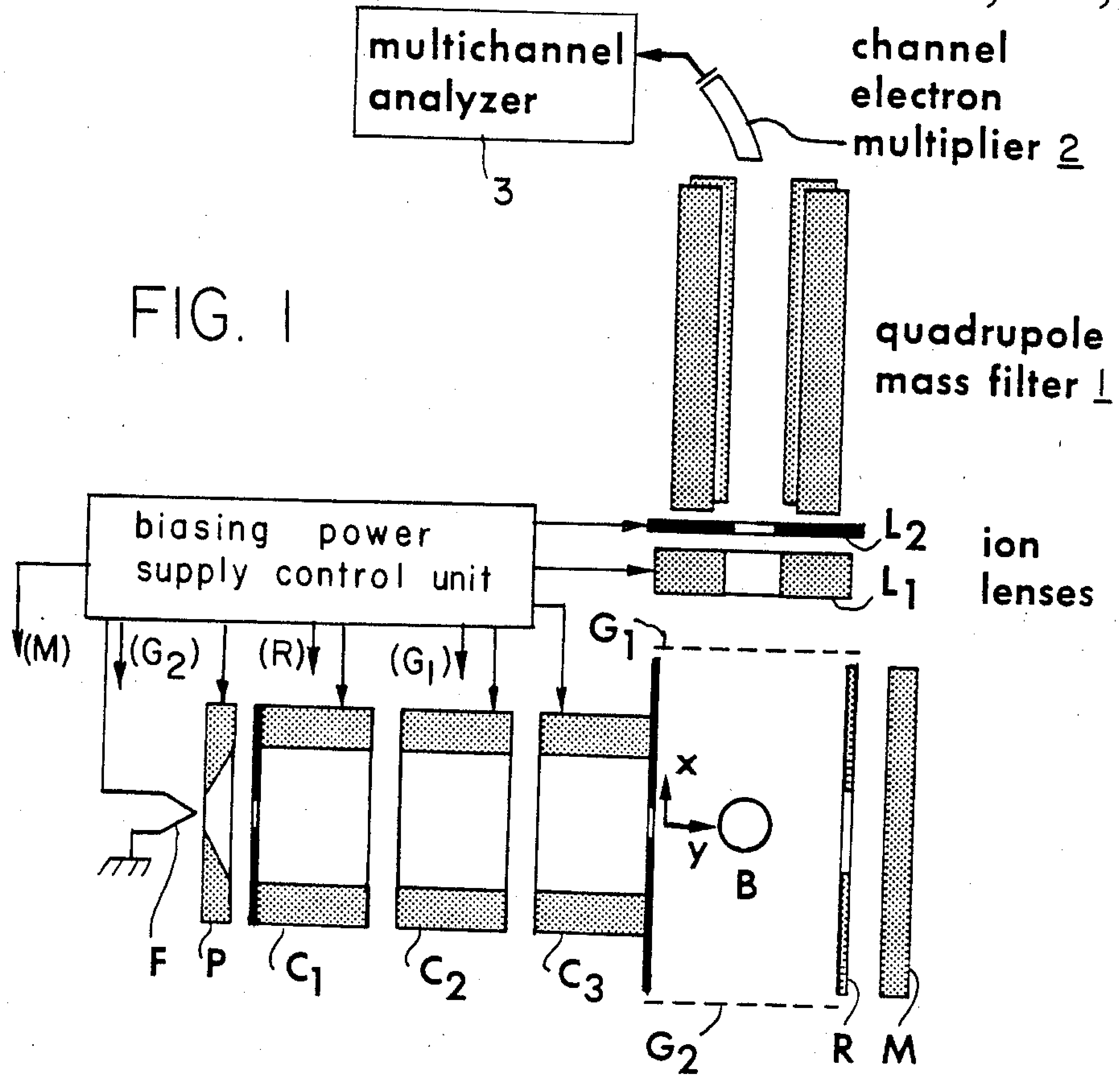


FIG. 1

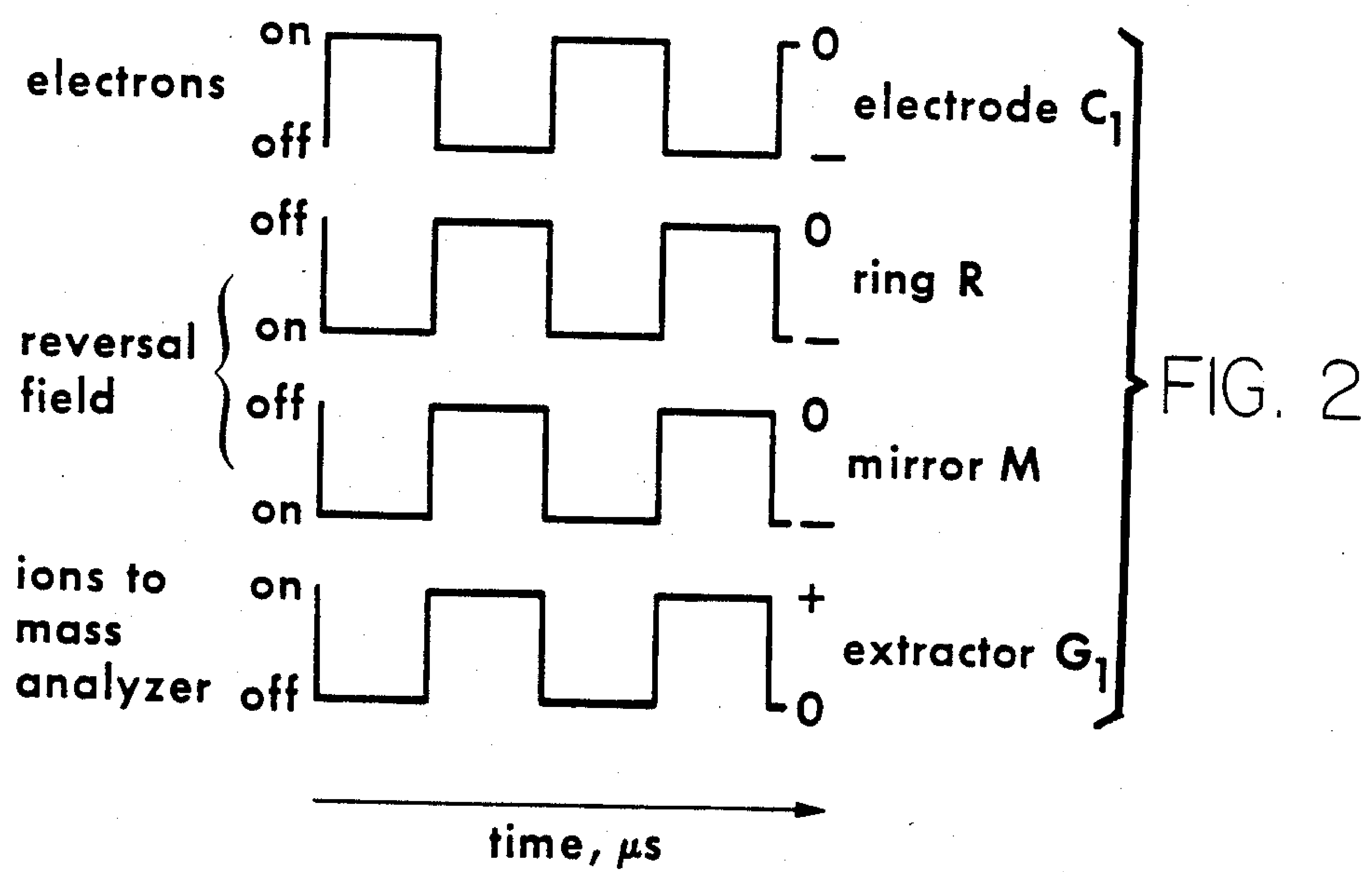


FIG. 2

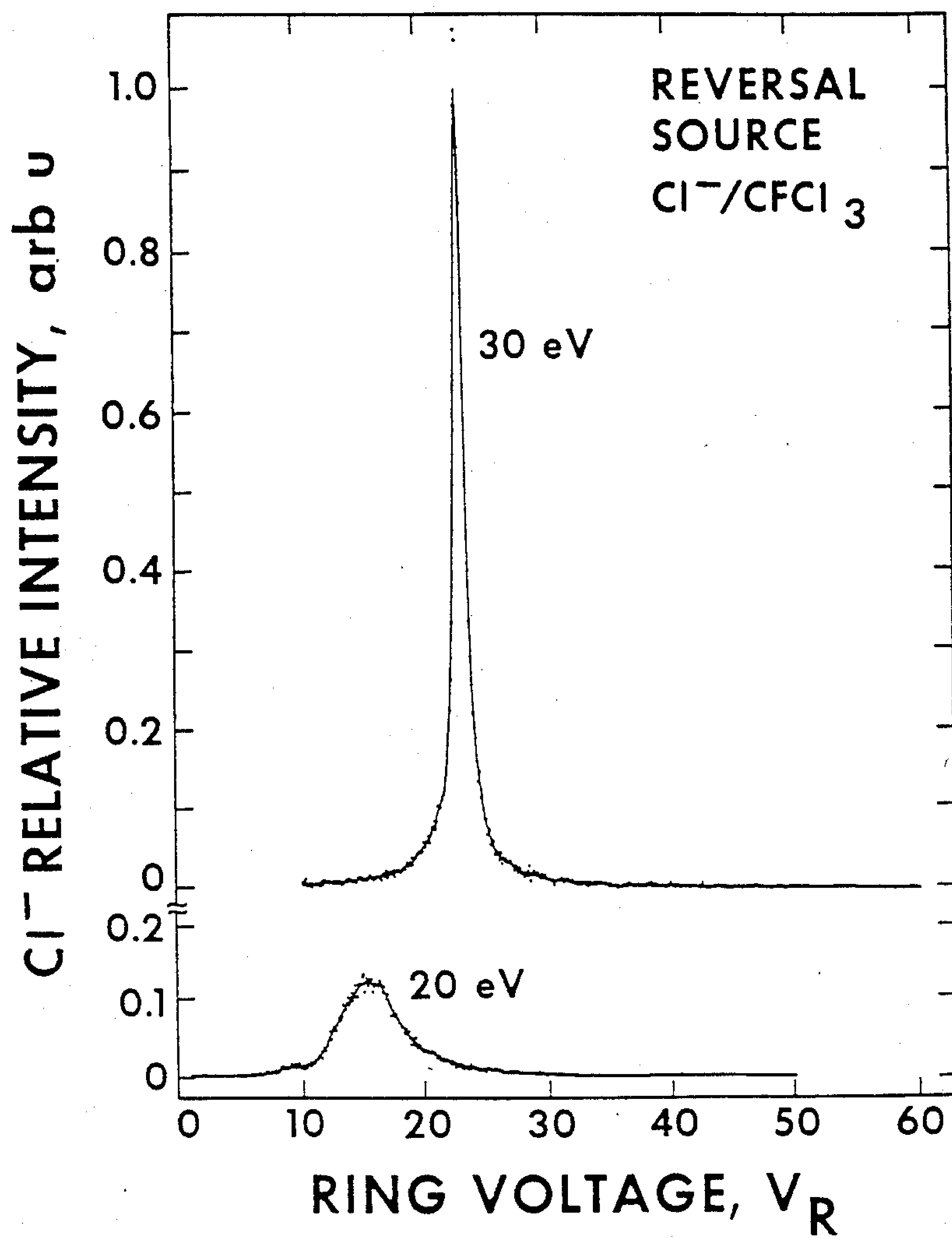


FIG. 3

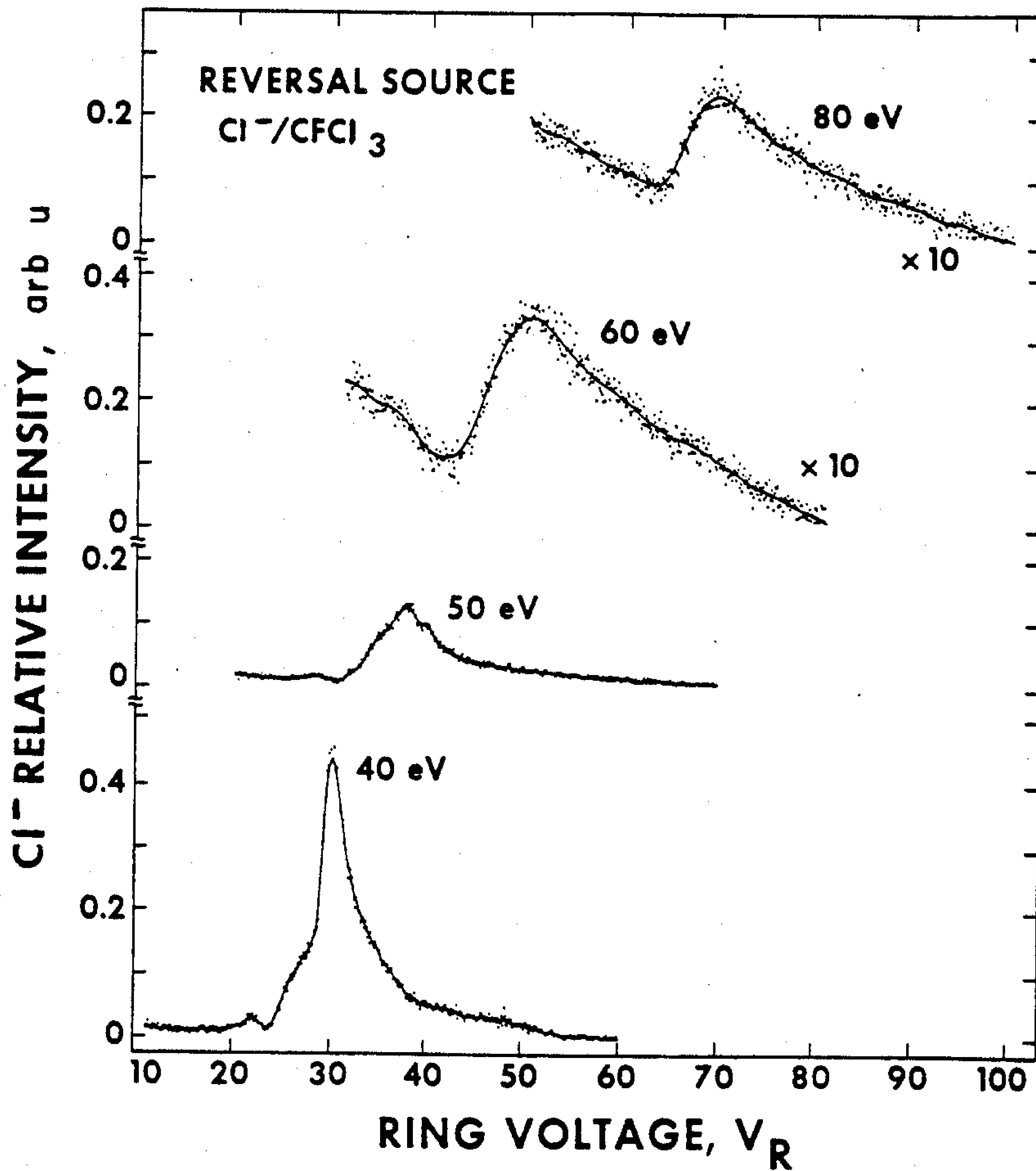


FIG. 4

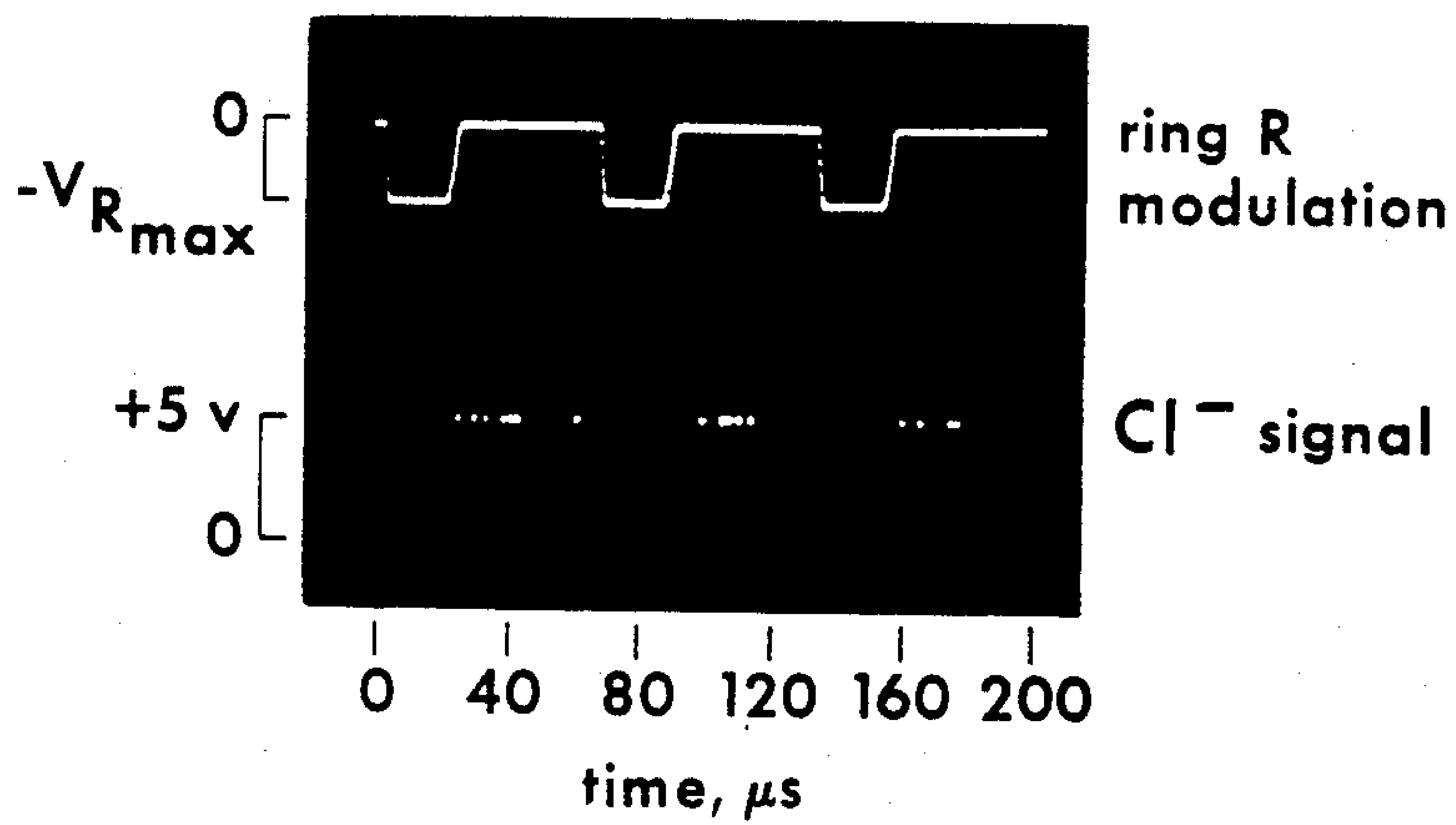


FIG.5

GENERATION OF INTENSE NEGATIVE ION BEAMS

ORIGIN OF INVENTION

The invention described herein was made in the performance of work under a NASA contract, and is subject to the provisions of Public Law 96-517 (35 USC 202) in which the Contractor has elected not to retain title.

BACKGROUND OF THE INVENTION

This invention relates to a method and apparatus for the generation of atomic and molecular negative ion beams, either pulsed or continuous beams.

The production of beams of atomic and molecular negative ions is of considerable interest in diverse areas of atomic, molecular, and plasma physics. Such beams are required for fusion plasma heating, heavy ion inertial-confinement fusion, and in basic atomic and molecular scattering studies. The types of sources for ion production are many and varied, involving both plasma and surface-plasma interactions.

SUMMARY OF THE INVENTION

In accordance with the present invention, an ion source utilizes a beam of electrons and target molecules. The source includes an electrode which reverses the electron beam, producing electrons at their turning point having a distribution of velocities centered at zero velocity. A gas which attaches zero velocity electrons or some near-zero velocity electrons is introduced at or near this turning point. Negative ions of the gas are produced by an attachment, or a dissociative attachment, process. For many of the thermal electron-attaching molecules, the attachment cross section at zero electron energy can be quite large, varying as (electron energy)$^{-\frac{1}{2}}$, or just the s-wave threshold law.

The novel features of the invention are set forth with particularity in the appended claims. The invention will best be understood from the following description when read in conjunction with the drawings.

BRIEF DESCRIPTION OF DRAWINGS

FIG. **1** is a schematic diagram of the apparatus and method for generation of intense beams of negative ions by zero-energy electron attachment, or dissociative attachment, in accordance with the present invention.

FIG. **2** illustrates the grid pulsing sequence for pulsed operation of the source shown in FIG. **1**.

FIG. **3** illustrates the relative Cl^- yields for continuous operation of the source shown in FIG. **1** as a function of the ring potential V_R, and at electron energies E_o of 20 eV and 30 eV.

FIG. **4** illustrates the relative Cl^- yields for continuous operation at 40, 50, 60, and 80 eV electron energies.

FIG. **5** illustrates the distribution of Cl^- pulses during several pulsing cycles of the ring electrode voltage V_{Rmax}.

DESCRIPTION OF PREFERRED EMBODIMENTS

In the following description, the cross sections referred to are "attachment cross sections" defined in the usual sense of the probability per molecule that an electron traversing a gas will undergo an attaching collision with the gas molecules.

Many molecules, such as SF_6, $CFCl_3$, perfluorinated carbon compounds, and chlorocarbon compounds, have extremely large cross sections for attachment of zero-energy electrons to form negative ions such as F^-, Cl^-, Br^-, and I^-. In conventional ion sources, electron energies are too high (of the order 2–3 eV or greater) to attach to these molecules. In the apparatus of the present invention, "zero energy" electrons are generated momentarily by pulsing a reversing electrode R negatively with respect to an electron-gun cathode F,P. In this preferred embodiment, the reversing electrode is comprised of a conductive ring R and a conductive mirror plate M. These electrons can then attach to molecules, such as $CFCl_3$, which effuse from a 1 mm diameter stainless-steel tube B placed at the center of the electrostatic reversal field. This field is produced by applying appropriate negative potential on the ring R and mirror M. The location of the electron turning point is governed by the magnitude of potentials on the electrodes R and M. Applying larger negative potentials E_R and E_M has the effect of moving the turning point to the left in FIG. **1**, and vice versa. The "mirror" effect produced by the ring R and mirror M can be either concave, convex or planar, depending upon the potential ratio. However, the invention is not limited to such an arrangement of these electrodes R and M as the "reversing electrode" for production of zero energy electrons.

The present invention takes advantage of the extremely large, threshold (zero-energy) electron attachment cross sections in several molecules to generate, for example, intense beams of F^-, Cl^-, Br^- and I^- ions. Thus, an ion source is provided in which an electrode or grid, which reverses electron trajectories, is placed just beyond an ion extraction aperture comprised of ion lenses L_1 and L_2. When the reversing electrodes are pulsed negatively, this pulse voltage reverses the direction of electrons momentarily, giving the electrons zero kinetic energy. At this zero-energy turning point the electrons attach to the ambient gas, and generate negative ions as the product of the attachment process. The method described herein as an example is applied to the generation of Cl^- ions from $CFCl_3$. Other ions from effusing molecules may be formed and extracted through the aperture formed by the ion lenses L_1 and L_2 in the same manner.

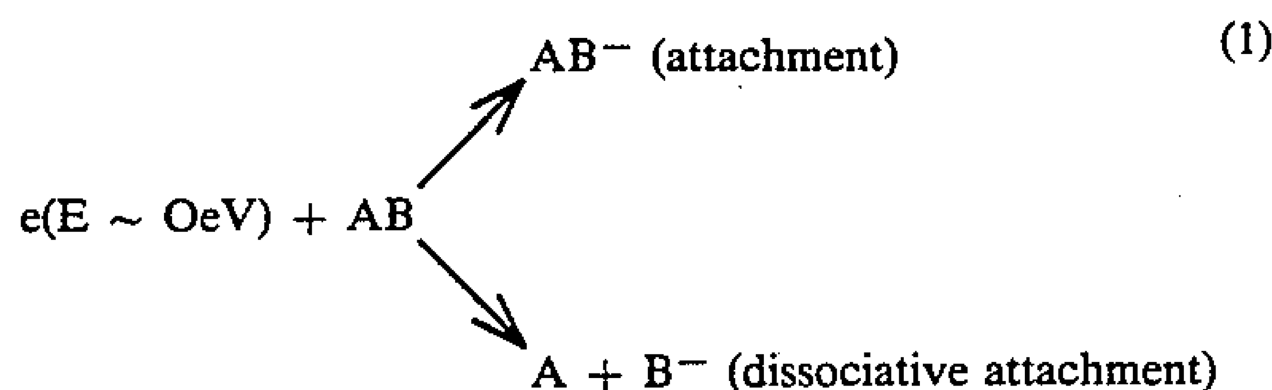
Recent experimental evidence has shown that the zero-energy cross section to $CFCl_3$, SF_6, CCl_4, and other molecules is much larger than previously expected. Thus, the probability of electron attachment during the field-reversal pulse will be much larger, making this apparatus an even more efficient ion source. Generally, the production yield of negative ions is the product of the electron energy distribution function and the dissociative attachment cross section, integrated over all electron energies. The reversing electrode momentarily creates a maximum in the distribution function at the maximum of cross section (zero eV), thus maximizing the integral and therefore the yield of negative ions.

The electrons in the turning point region B will have a peak at about zero eV in their energy distribution. These electrons can then attach to an admixed gas having a peak in its dissociative attachment (DA) cross section at zero eV. Cl^- was generated as an example from $CFCl_3$ for several reasons: the behavior of the cross section for Cl^- production at zero eV (greater than 10^{-13} cm^2) is now well known, and is many orders

of magnitude greater than for H^- production from H_2 at higher energies, an effect due to the divergent nature of the s-wave attachment cross section; Cl^- is by far the major ion produced in $CFCl_3$ at any electron energy; and $CFCl_3$ is inexpensive and inert.

Other examples of the effect of reversal of electron trajectories is seen in a high-pressure electron swarm and the diffuse discharge plasmas. Electrons in a swarm, for example are backscattered by elastic and inelastic gas collisions. These electrons move against the drift field until their trajectories are reversed, and are accelerated along the field lines again. At their turning point, they have essentially zero kinetic energy, and can be removed from the swarm by attachment to SF_6, I_2, or an admixed perfluorocarbon compound.

The overall process can be described, for molecules AB and electron energy E, as



From the Wigner threshold law, the cross section to form the atomic ions Cl^- or F^-, or the corresponding parent negative ions, behaves as $E^{-\frac{1}{2}}$ in the limit $E \rightarrow 0$, thus providing an extremely efficient path for negative ion formation. Use of $CFCl_3$ had the additional virtue that the cross section for Cl^- production greatly exceeded that for production of other possible ions (F^-, Cl_2^-, and CCl_3^-) at energies below 3 eV. This situation arises in other molecular targets as well, and makes for an efficient source with minimal interference from other species during extraction and acceleration in an ion beam transport system.

The theoretical calculation of Henkelman and Ottensmeyer, J. Phys. E7, 176 (1974), is used to fix the placements of the C_3, M, and R electrodes, and to determine the aperture diameters in C_3 and R. The distance between C_3 and R was 9.8 mm in our experiments.

Assuming the origin as the center of the aperture in C_3 and neglecting aberrations in the reversal field, the longitudinal energy E_y and transverse energy E_x are

$$E_y = E_{oy} - e|\epsilon \cdot y|$$

$$E_x = E_{ox}, \quad (2)$$

where ϵ is the electric field intensity, and E_{0x} and E_{0y} ($E_0 = E_{0x} + E_{0y}$) refer to launched values of electron energy at the origin. The total energy at any location is $E = E_x + E_y$ and diminishes with increasing electron penetration into the field. The mean transverse energy E_x is $E_0 \sin^2\theta$, where the θ is the mean divergence angle in the electron gun. The particular case chosen in $E_y = 0$ located at $y = |E_{0y}/e\epsilon|$, although one may choose other energies as well.

The grids G_1 and G_2 serve to extract out of the reversal field the negative ions (here Cl^-) generated. The bias on G_1 is positive, and that on G_2 negative relative to ground. The extracted ions are accelerated by several lenses formed by electrodes L_1 and L_2, and focused at the entrance aperture of a utilization device (here a quadrupole mass filter **1** tuned to the mass of the particular negative-ion fragment in the experiments). After mass filtering the ions are accelerated to 1 keV into a channel-type electron multiplier **2**. The output of the multiplier is amplified, and stored by multichannel analyzer **3** as a function of either sweep voltage on the ring element R, or as a function of incident electron energy E_0. The base pressure of the vacuum system (about 2×10^{-5} Pa) rose to a background pressure of 2×10^{-3} Pa during operation.

The extraction of Cl^- ions may be carried out in either a continuous or pulsed mode. In the case of continuous operation, steady-state potentials are applied to the electron gun element C_1 and extracting electrodes G_1,G_2. In practice there is negligible penetration of the G_1, G_2 fields into the region B so that ions extracted in this way are very likely only a small part of the total ion production in the turning point region.

In pulsed operation ions are formed by applying the appropriate potentials to elements C_1, R and M to turn the ion beam on, and reverse it in the region B, for periodic intervals, and then applying the appropriate potential at a grid G_1 for extraction of the negative ions while the electron beam and reversal field are pulsed off. The sequence of applied pulses is shown in FIG. **2**. Elements G_1 and G_2 are held at ground potential during the ion generation interval. The Cl^- ions are created via a dissociative attachment process $e(E \sim 0 \text{ eV}) + AB \rightarrow A + B^-$ in this step. The electron gun is then pulsed off by applying a -100 V potential to electrode C_1 and grounding the mirror M and ring R. A positive pulse is applied to grid G_1 to extract the Cl^- ions (while a negative pulse is applied to grid G_2). These ions are extracted through an aperture formed by ion lenses L_1 and L_2, and mass analyzed. For these experiments, the ion pulses from the channel-type detector were routed to the multi-channel analyzer where the ion signal is stored as a function of E_0, or the ring and mirror voltages, as part of an experimental test of the invention.

Experimental Results

We have measured the negative ion yield as a function of ring potential at incident electron energies E_0 of 20, 30, 40, 50, 60 and 80 eV. In the case of continuous operation the mirror potential V_m at each energy was just $-E_0/e$ (where e is the magnitude of electron charge) and the potential V_R on R was obtained from the calculations of Henkelman and Ottensmeyer, supra for the ratio V_R/V_M.

Results of Cl^- signal vs V_R for continuous-mode operation are shown in FIGS. **3** and **4** at the indicated E_0. It is clear from these spectra that, as expected, increasingly greater ring voltages V_R are required to reverse increasingly energetic electron (higher E_0). Also, the highest signal count rates and narrowest widths were encountered as $E_0 = 30$ eV. While this effect of width is not clearly understood, several effects which could give rise to this behavior with E_0 are: optimum electron-molecule spatial overlap (e.g., focusing at region B the smaller "disk of least confusion" rather than the Gaussian image), a minimal transverse energy E_x, thus bringing more electrons into the peak of the attachment cross section at zero electron energy (see Eq. 2), minimal aberrations in the reversal field, or optimal extraction and focusing efficiency by G_1, L_1, and L_2.

All count rates in FIGS. **3** and **4** are given relative to the 30 eV count rate, so that relative efficiencies at the different energies can be compared. In the following table we list at each energy the peak counting rate,

integral counting rate, and the mirror ratio V_{Rmax}/V_M corresponding to the peak signal.

Incident Electron Energy E_o (eV)	Maximum Counting Rate (10^2/sec)	Integral Counting Rate (10^4/sec)	$\frac{V_{Rmax}}{V_M}$
20	2.2	1.6	0.75
30	18.0	3.2	0.75
40	7.6	5.2	0.75
50	5.7	2.5	0.75
60	0.58	1.4	0.81
80	0.47	1.1	0.87

For pulsed operation of the source described hereinbefore with reference to FIG. 2 there is shown in FIG. 5 an oscilloscope image of the distribution of Cl^- pulses during several cycles of the ring voltage V_{Rmax}. The electron energy is 40 eV and the value V_{Rmax}/V_M is 0.75. The maximum yield and peak-integrated yield for this pulsed operation is found to be about ten times greater than for continuous operation, even after a 30% duty cycle is taken into account. This increase is almost certainly due to the fact that Cl^- ions are now being extracted from a field-free region, and not from the field of the ring and mirror which tends to drive the ions from the turning point region back toward C_3.

Efficiency

The production rate I of Cl^- ions can be written as

$$I(Cl^-)(s^{-1}) = NV\phi\sigma_A(E), \quad (3)$$

where N(cm^{-3}) is the $CFCl_3$ target density, V(cm^3) the overlap volume between the electron and target beams, $\phi(s^{-1}\,cm^{-2})$ the incident electron flux, and $\sigma_A(E)(cm^2)$ the attachment cross section at $E\sim 0$ energy. Estimates of the quantities in Eq. (3) are as follows: A pressure of $CFCl_3$ in the beam was taken as 0.133 Pa, or $N\sim 3.3\times 10^{-}cm^{-3}$. The interaction volume is taken as that of a cylindrical electron beam of 0.2 cm diameter intersecting a target beam of 0.2 cm diameter, or $V\sim 6.3\times 10^{-3}$ cm^3. The electron flux is taken as a 1.5 μA electron beam in a cylinder of 0.2 cm diameter or 3.0×10^{14} s^{-1} cm^{-2}, and an average attachment cross section is taken as 2×10^{-14} cm^2 for E less than approximately 0.1 eV. Assuming that the entire 1.5 μA incident current is reversed to give a sum of longitudinal and transverse energies E of less than about 0.1 eV, then the production rate I(Cl^-) is 1.2×10^{12} s^{-1}, or 0.2 μA. Thus, it appears that 13% of the incident electron beam can be converted to Cl^-. This corresponds to a current density ρ of $\rho\sim 0.2\ \mu A/3\times 10^{-2}=6.7\ \mu A/cm^2$ for emission from a 0.2 cm diam region of the target. This density can be increased by several orders of magnitude through use of (a) more intense electron beams (milliamperes or amperes as opposed to microamperes currently used) with a correspondingly larger beam size, and (b) denser targets.

It should also be possible to extend the use of the source to the generation of negative ions through attachment resonances located at nonzero electron energies, since a continuous distribution of electron energies exists between C_3 and R. While for the present demonstration of the source we have chosen $E_y=0$, one can choose (see Eq. 2) any other energy E'_y located at the same y, but at a value of

$$\epsilon' = |(E_{0y}-E'y)/ey| \quad (4)$$

This energy could correspond, for example, to the 3.7 $eV\,^2\Sigma_u$ resonance in H_2 to produce H^-. Moreover, any given energy E'_y is attained twice: once when ϵ' and y are parallel (electrons decelerating towards the turning point), and once when antiparallel (electrons accelerating away from the turning point). Thus, the electron beam is "used" twice.

What is claimed is:

1. A method for generating negative ions using a beam of electrons comprising the steps of:

producing an electric field in the path of said electron beam for reversal of said electron beam to produce at the turning point electrons having a distribution of energies centered at zero;

introducing a gas containing thermal electron-attaching molecules at a point in the path of said electron beam where said electrons have a low energy and a high probability for attachment to said molecules, thereby efficiently generating ions; and

directing said ions in a focused beam to a utilization device.

2. A method as defined in claim **1** for generating negative ions from thermal electron-attaching molecules having an extremely large attachment cross section at zero electron energy wherein said gas of said molecules is introduced at said turning point.

3. A method as defined in claim **1** for generating negative ions from thermal electron attaching molecules having an attachment cross section at a level near zero electron energy wherein said gas of said molecules is introduced at a point in the path of said electron beam ahead of said turning point, whereby said electrons of the appropriate energy make two passes through said gas of said molecules for enriched ion generation.

4. A method as defined in claim **1** wherein said electric field is controlled to be constant for continuous generation of ions.

5. A method as defined in claim **1** wherein said electric field is controlled for pulsed generation of ions.

6. A method as defined in claim **5** wherein said control of said electric field for pulsed generation of ions includes pulsed gating of said beam of electrons to said turning point and simultaneously pulsing said reversal of said electron beam while said electron beam is gated on, and directing said ions to said utilization device while reversal of said electron beam, and the generation of said electron beam, are pulsed off.

7. A negative ion source comprising:

means for generating a beam of electrons, electrodes in the direct path of said beam;

means for biasing said electrodes for reversal of said electron beam to produce at the turning point electrons having a distribution of energies centered at zero;

means for introducing a gas containing thermal electron-attaching molecules at a point in the path of said electron beam where said electrons have low energy and a high probability for attachment to said molecules, thereby efficiently generating ions; and

means for directing said ions in a focused beam to a utilization device.

8. Apparatus as defined in claim **7** for generating negative ions from thermal electron-attaching molecules having an extremely large attachment cross sec-

tion at zero electron energy wherein said gas of said molecules is introduced at said turning point.

9. Apparatus as defined in claim **7** for generating negative ions from thermal electron-attaching molecules having an attachment cross section at a level near zero wherein said gas of said molecules is introduced at a point in the path of said electron beam between said electron gun and said turning point, whereby said electrons of the appropriate energy make two passes through said gas of said molecules for enriched negative ion generation.

10. Apparatus as defined in claim 7 wherein said biasing means is controlled with constant voltages for continuous generation of ions.

11. Apparatus as defined in claim 7 wherein said biasing means is controlled for pulsed generation of ions.

12. Apparatus as defined in claim **11** wherein said control of said biasing means for pulsed generation of ions is comprised of means for pulsed gating of electrons to said turning point and simultaneously pulsing said electrodes for reversal of said electron beam while said electron beam is turned on, and turning on said means for directing said ions to said utilization device while said electrodes for reversal of said electron beam, and said electron beam, are pulsed off.

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